

Neutrinos in  
the 21<sup>st</sup>  
Century

Mary Bishai  
Brookhaven  
National  
Laboratory

A Brief  
History of  
Neutrinos

Measurement  
of Neutrino  
Mass

Neutrino  
Mixing Expts -  
Current

The Search for  
 $\theta_{13}$

CP Violation  
and the Mass  
Hierarc

DUSEL/LBNE  
Neutrino Expts.  
in Japan

Superbeams in  
Europe

# Neutrinos in the 21<sup>st</sup> Century

## 2010 RHIC & AGS Annual Users Mtg

Mary Bishai  
Brookhaven National Laboratory

June 7, 2010

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# Neutrino Conception

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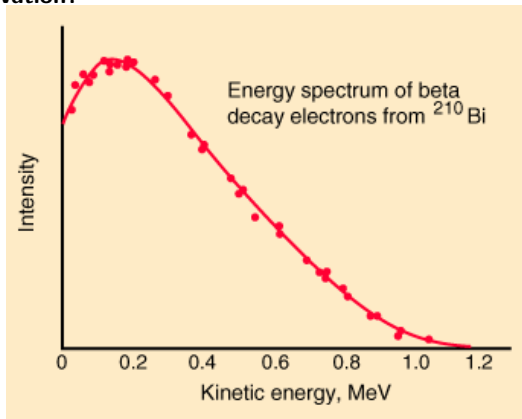
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Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



G.J Neary, Proc Phys. Soc., A175, 71 (1940)

Dec 1930: **Wolfgang Pauli's** letter to physicists at a workshop in Tübingen proposes that a neutrally charged "neutron" **with a mass** " **$< 0.01$  proton mass**" is emitted in beta-decays.

# Finding Neutrinos...

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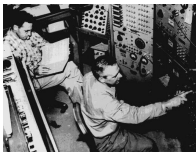
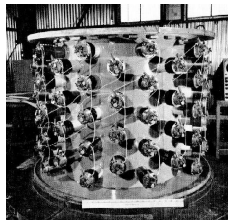
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**1950's: Fred Reines at Los Alamos and Clyde Cowan** mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with **water with  $\text{CdCl}_2$  in solution** was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:

- 1  $\bar{\nu}_e + p \rightarrow n + e^+$
- 2  $e^+ + e^- \rightarrow \gamma\gamma$  ( $2 \times 0.511 \text{ MeV} + T_e^+$ )
- 3  $n + {}^{108}\text{Cd} \rightarrow {}^{109}\text{Cd}^* \rightarrow {}^{109}\text{Cd} + \gamma$   
( $\tau = 5\mu\text{s}$ ).



*Neutrinos first detected using a nuclear reactor!*

# Neutrinos have Flavors

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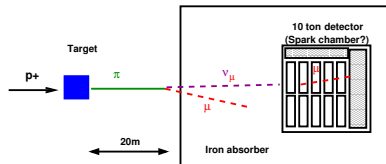
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**1962:** Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay  $\pi \rightarrow \mu \nu_x$



The AGS



Making  $\nu$ 's

**Result:** 40 neutrino interactions recorded in the detector, 6 of the resultant particles were identified as background and 34 identified as

$\mu \Rightarrow \nu_x = \nu_\mu$

*The first accelerator neutrino experiment was at the AGS.*

# The Homestake Experiment

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**1967:** **Ray Davis** from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

- 1  $\nu_e^{\text{sun}} + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$ ,  $\tau({}^{37}\text{Ar}) = 35$  days.
- 2 Number of Ar atoms  $\approx$  number of  $\nu_e^{\text{sun}}$  interactions.



Ray Davis

**Results: 1969 - 1993 Measured  $2.5 \pm 0.2$  SNU** (1 SNU = 1 neutrino interaction per second for  $10^{36}$  target atoms) while theory predicts 8 SNU. This is a  **$\nu_e^{\text{sun}}$  deficit of 69%**.

**Solar  $\nu_e$  disappearance  $\Rightarrow$   
first experimental hint of oscillations**

# Neutrino Mixing: 3 flavours

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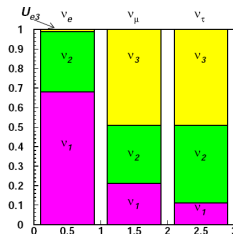
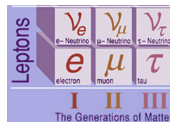
**We know now of 3 flavours of neutrinos:** The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

**In the past 10 yrs we have measured most of the  $U_{\text{PMNS}}$  parameters**

$$U_{\text{PMNS}} \sim \begin{pmatrix} 0.8 & 0.5 & < 0.20 ?? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, \mathbf{V}_{\text{CKM}} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

**In contrast to CKM, large off diagonal terms:**



# The Super-Kamiokande Experiment

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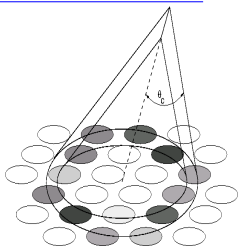
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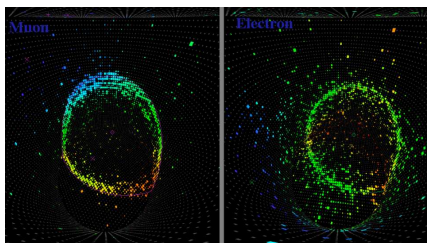
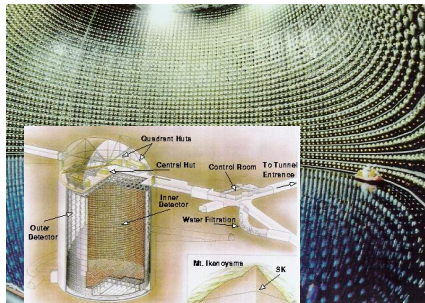
Superbeams in  
Europe

A huge **50kT double layered tank of ultra pure water** surrounded by 11,146 20" diameter photomultiplier tubes. Located in an old zinc mine 0.6km under Mount Ikena in the Japanese Alps, near the town of Kamioka. The project has been collecting data since 1 April 1996.



Particle id using rings of

Čerenkov light



# Super-Kamiokande: Atmospheric $\nu_\mu$ Disappearance

$2 \leftrightarrow 3$  mixing

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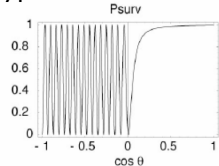
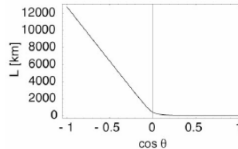
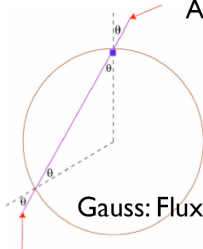
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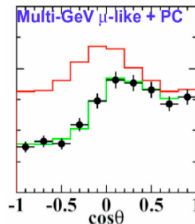
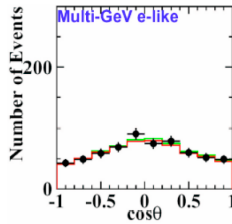
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Atmospheric neutrinos as a source for oscillation experiments

Atm. neutrinos 2:1  $\mu$ :e type



Gauss: Flux inside spherical shell isotropic



Evidence for neutrino oscillations from SuperK

**1998-present: SuperKamiokande measures atm. neutrino oscillations.**

# 3-Neutrino Mixing

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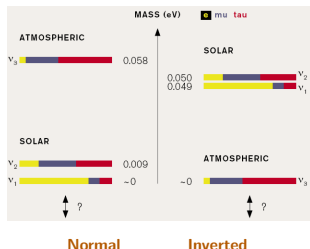
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$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \rightarrow \nu_e, \text{ reactor } \bar{\nu}_e \text{ disappear}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e, \bar{\nu}_e \text{ disappear}}$$

where  $c_{ij} = \cos \theta_{ij}$  and  $s_{ij} = \sin \theta_{ij}$ .

**$\sin^2 \theta_{13}$ :** Amount of  $\nu_e$  in  $\nu_3$   
 **$\tan^2 \theta_{12}$ :**  $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

**$\tan^2 \theta_{23}$ :** Ratio of  $\frac{\nu_\mu}{\nu_\tau}$  in  $\nu_3$



There are 3 quantum states mixing  $\Rightarrow$   
 there is an overall phase:  $\delta_{\text{CP}}$ .

If  $\delta_{\text{CP}} \neq 0$  or  $\pi$ , charge-parity (CP) is  
 violated and there is a  $\nu/\bar{\nu}$  asymmetry.

Could this explain the origin of matter?

Is  $\sin^2 2\theta_{13} = 0$ ? (no CP violation)

What is the value of  $\delta_{\text{CP}}$ ,  $\text{sign}(\Delta m_{31}^2)$ ?

# Measuring neutrino mixing - $\nu_e$ oscillations

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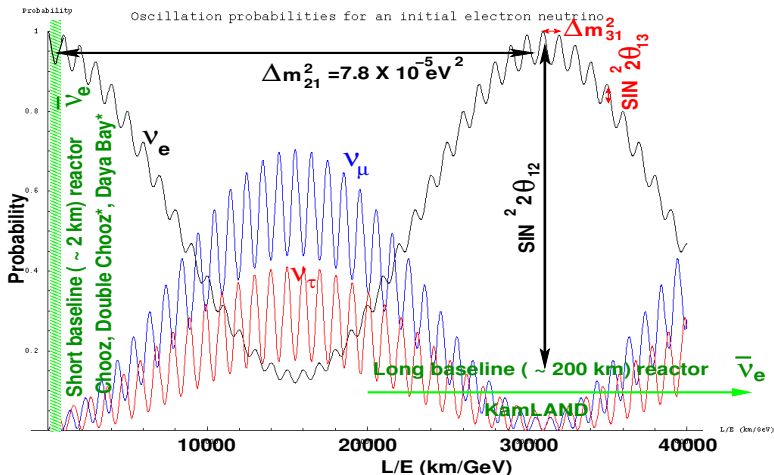
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Solar  $\nu_e$  disappearance constrained  $1 \rightarrow 2$  mixing. Precision from reactor  $\bar{\nu}_e$  experiments:



\* = future reactor  $\bar{\nu}_e$  experiments

# Measuring $\nu_\mu$ oscillations - Accelerator Expts

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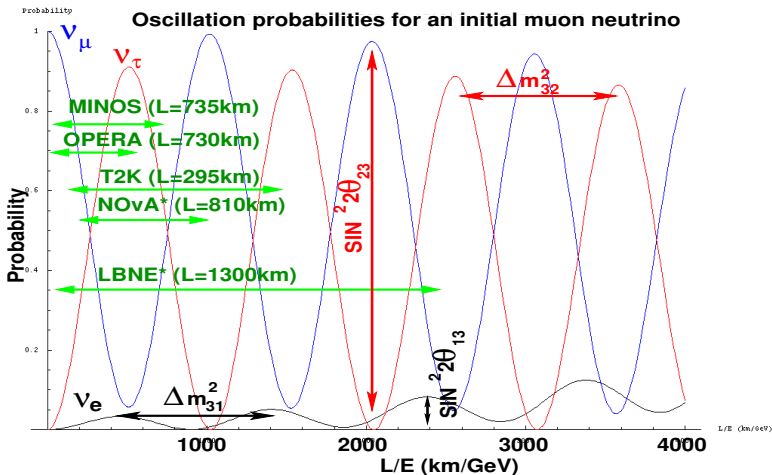
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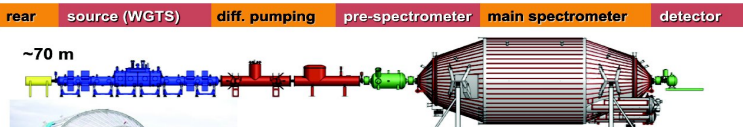


Accelerator expts access all 3-state oscillations using known  $\nu/\bar{\nu}$  fluxes.

Can provide precision measurements of  $\Delta m_{31,32}^2$ ,  $\sin^2 2\theta_{13}$ ,  $\delta_{cp}$

# Measurement of Neutrino Mass

## Tritium end point : KATRIN



08/04/08

Chris Walter ICHEP08

Test spectrometer: 2009  
Start measurements: 2010  
5 years run sensitivity (0.2 eV/c<sup>2</sup>)

19

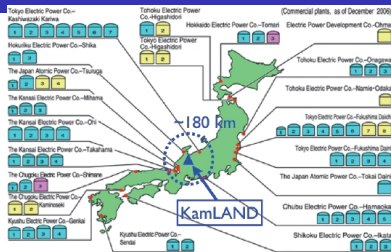
## $0\nu\beta\beta$ decay

- **GERDA (CNGS):** Uses  ${}^76\text{Ge}$ ,  $Q_{\beta\beta} = 2.039\text{ MeV}$ . Ge diodes with LAr and water shields. Phase II sensitivity:  
 $T_{1/2} > 1.5 \times 10^{26}\text{y}$ ,  $\langle m_{\beta\beta} \rangle < 0.2\text{eV}$
- **EXO (WIPP):** LXe 80% enriched  ${}^{136}\text{Xe}$ . 200 kg prototype run for 2 yrs:  
 $T_{1/2} > 6.5 \times 10^{26}\text{y}$ ,  $\langle m_{\beta\beta} \rangle < 0.13 - 0.19\text{eV}$

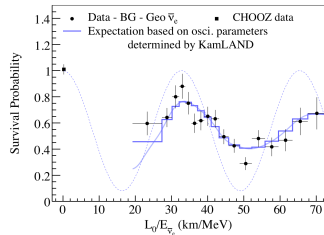
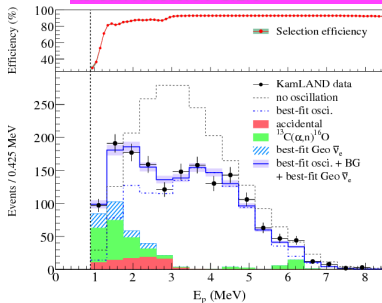
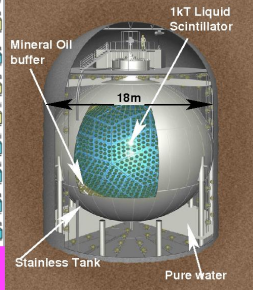
# The KamLAND $\bar{\nu}_e$ Reactor Experiment

# Neutrinos in the 21<sup>st</sup> Century

## Neutrino Mixing Expts - Current



World reactors + Research reactors : 0.96%  
Korean reactors : 3.2%

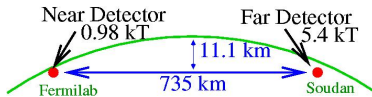


# The NuMI/MINOS Accelerator $\nu_\mu$ Experiment

The longest baseline accel.  $\nu$  expt in operation. Average power = 320 kW.

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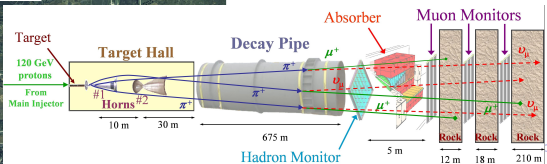
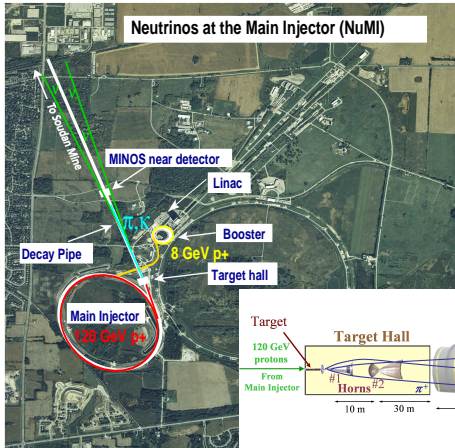
Fermi Natl. Lab., IL

Soudan Underground Lab, MN



NuMI Horn 2 inner conductor  
Radial field,  $B \propto 1/r$

3T at 200 kA



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# The MINOS Detectors

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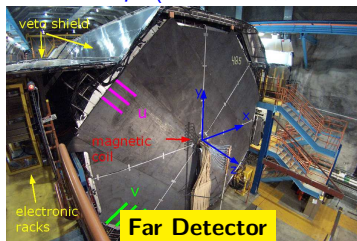
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*Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips (1 cm thick, 4.1 cm wide) readout by WLS fiber.*



- 484 octagonal steel and scintillator plates 8m wide,  
⇒ 5.4kTon and 30 m in length
- Toroidal B-field, 1.3 T at  $r = 2\text{m}$
- Cosmic  $\mu$  veto shield
- 282 “squashed” octagonal steel plates, 153 scintillator planes.  
⇒ 1kTon and 16 m in length
- Toroidal B-field, 1.3 T at  $r = 2\text{m}$

# MINOS Results - 2009 ( $3.5 \times 10^{20}$ protons-on-target)

The NuMI beam contains 91.5%  $\nu_\mu$ , 7 %  $\bar{\nu}_\mu$  and 1.5%  $\nu_e + \bar{\nu}_e$

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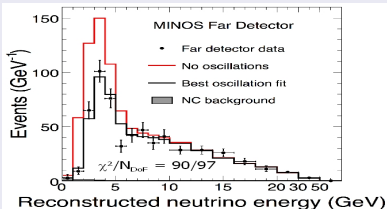
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## $\nu_\mu$ disappearance

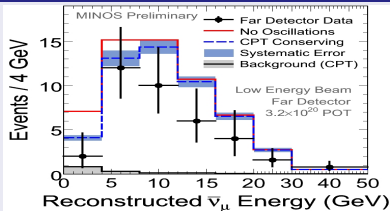
PRL 101, 2008



Expected no-osc  $1065 \pm 60$ .

**Observe 848.**

## $\bar{\nu}_\mu$ disappearance

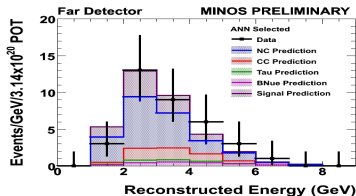


Expected (with osc)  $58.3 \pm 7.6_{\text{stat}} \pm 3.6_{\text{sys}}$ .

**Observe 42.**

## $\nu_e$ appearance

PRL 103, 2009



Expected FD background:  $27 \pm 5_{\text{stat}} \pm 2_{\text{sys}}$ .

**Observe 35.**

## MINOS results 2009:

### $\nu_\mu$ Disappearance:

$$\Delta m_{32}^2 = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2 \quad \text{5\% accuracy}$$

$$\sin^2 2\theta_{23} > 0.90 (90\% \text{ C.L.})$$

### $\bar{\nu}_\mu$ Disappearance:

$$\text{Fraction } \nu_\mu \rightarrow \bar{\nu}_\mu < 0.026 (90\% \text{ C.L.})$$

### $\nu_e$ appearance:

$$\sin^2 2\theta_{13} < 0.29 (90\% \text{ C.L.}); \Delta m^2 > 0, \delta_{\text{CP}} = 0$$

$$\sin^2 2\theta_{13} < 0.42 (90\% \text{ C.L.}); \Delta m^2 < 0, \delta_{\text{CP}} = 0$$

**Search for  $\nu_s$**

# MINOS Results - 2009 ( $3.5 \times 10^{20}$ protons-on-target)

The NuMI beam contains 91.5%  $\nu_\mu$ , 7 %  $\bar{\nu}_\mu$  and 1.5%  $\nu_e + \bar{\nu}_e$

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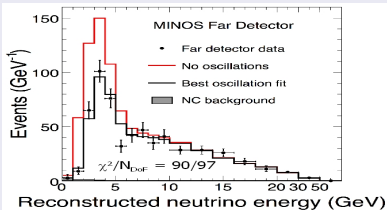
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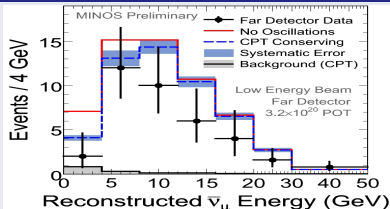
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**Observe 848.**

## $\bar{\nu}_\mu$ disappearance



Expected (with osc)  $58.3 \pm 7.6_{\text{stat}} \pm 3.6_{\text{sys}}$ .

**Observe 42.**

## Coming soon: $\nu_e$ appearance 2010

Expect  $3\sigma$  sensitivity at  
 $\sin^2 2\theta_{13} = 15\%$

**Lisa Whitehead, BNL Colloquium  
4/9/2010**

## MINOS results 2009:

### $\nu_\mu$ Disappearance:

$$\Delta m_{32}^2 = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2 \quad \text{5\% accuracy}$$

$$\sin^2 2\theta_{23} > 0.90 (90\% \text{ C.L.})$$

### $\bar{\nu}_\mu$ Disappearance:

$$\text{Fraction } \nu_\mu \rightarrow \bar{\nu}_\mu < 0.026 (90\% \text{ C.L.})$$

### $\nu_e$ appearance:

$$\sin^2 2\theta_{13} < 0.29 (90\% \text{ C.L.}); \Delta m^2 > 0, \delta_{\text{CP}} = 0$$

$$\sin^2 2\theta_{13} < 0.42 (90\% \text{ C.L.}); \Delta m^2 < 0, \delta_{\text{CP}} = 0$$

**Search for  $\nu_s$**

# The mixing matrix - 2009

J. Valle, TAUP '09

Maltoni et al, NJP 6 (2004) 122

Schwetz et al, NJP 10 (2008) 113011

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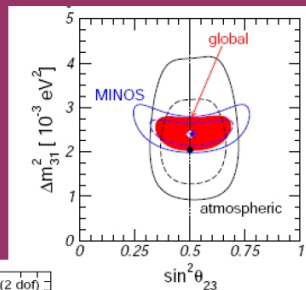
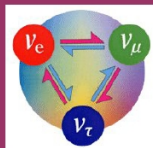
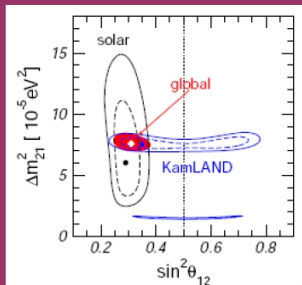
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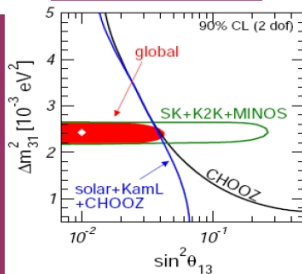
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**Homestake, SAGE+  
GALLEX/GNO,  
Super-K, SNO  
Borexino**

**KamLAND (180 Km)**

Valle@TAUP09



... Super-K

**K2K (250 Km)  
MINOS (735 Km)**

# The Daya Bay Reactor Complex

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## Reactor Specs:

**Located 55km north-east of Hong Kong.**

**Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW<sub>th</sub>**

**By 2011: 2 more cores at Ling Ao II site = 17.4 GW<sub>th</sub> ⇒ top five worldwide**

**$1 \text{ GW}_{th} = 2 \times 10^{20} \bar{\nu}_e / \text{second}$**

**Deploy multiple near and far detectors**

**Reactor power uncertainties < 0.1%**

# The Daya Bay Experiment

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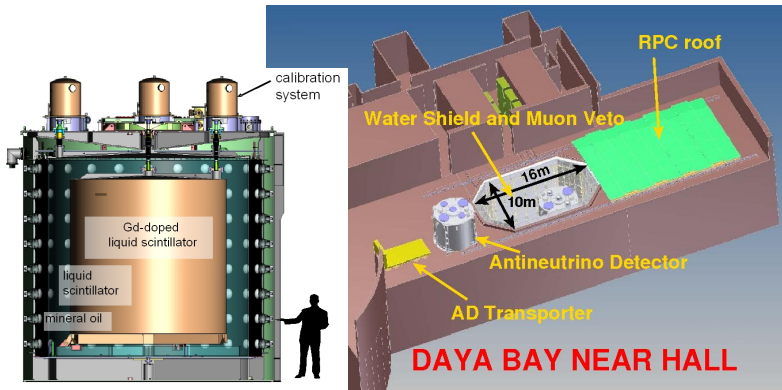
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- Multiple “identical” detectors at each site.
- Manual and multiple automated calibration systems per detector.
- Thick water shield to reduce cosmogenic and radiation bkgds.

	DYB	LA	Far
Event rates/20T/day	840	740	90

# Daya Bay Sensitivity

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Source of uncertainty		Chooz (absolute)	Daya Bay (relative)	Strategy
# protons	H/C ratio	0.8	< 0.1	Fill in pairs/calib
	Mass	-	< 0.3	Load cells and mass flowmeters
Detector Efficiency	Energy cuts	0.8	0.2	lower threshold/calib
	Position cuts	0.32	0.0	3-zone
	Time cuts	0.4	0.1	Common clock ~ 10ns
	H/Gd ratio	1.0	0.1	fill in pairs/calib
	n multiplicity	0.5	0.05	Deeper/muon veto
	Trigger	0	0.01	Redundant triggers
	Live time	0	< 0.01	Common GPS clock
Total detector-related uncertainty		1.7%	0.38%	

End 2010: Near detector ready. End 2011: far detectors ready

Reach sensitivity to  $\sin^2 2\theta_{13} < 0.01$  @ 90% C.L. by 2014

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# The Double Chooz Experiment

M. Dierckxsens, TAUP'09

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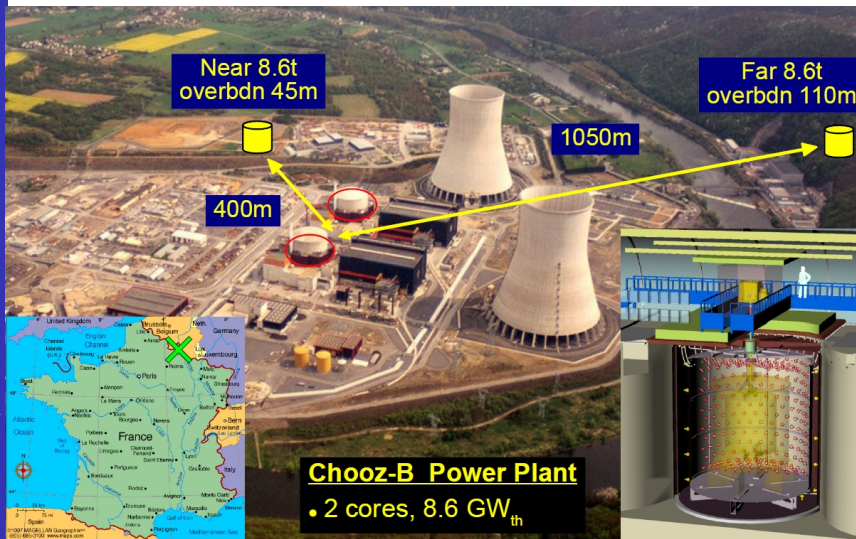
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**Spring 2010: Far detector ready. End 2010: near detector ready**

# Off-axis high intensity $\nu_\mu$ beams: T2K

30-50 GeV p accel, designed for 750 kW, started operations 2009

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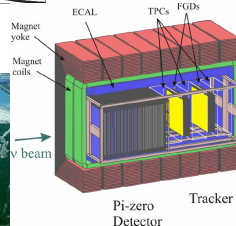
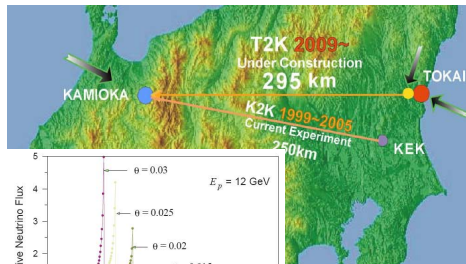
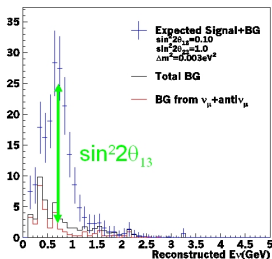
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**First proposed for BNL  
E-889 (1995):** A narrow  
beam of  $\nu_\mu$  can be achieved  
by going off-axis to the  $\pi$   
beam. **Better S:B at  
oscillation max.**

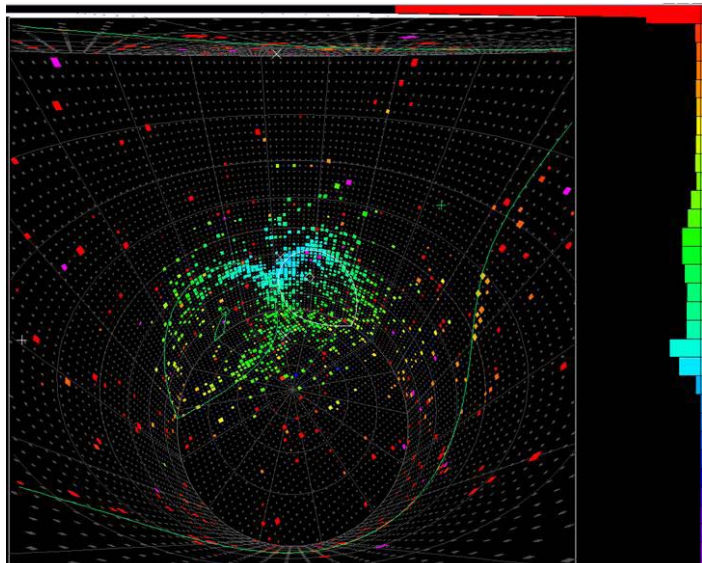
**Expected  $\nu_e$  appearance  
signal at  $\sin^2 2\theta_{13} = 10\%$ :**



**Goal: search for  $\nu_\mu \rightarrow \nu_e$  with sensitivity to  $\sin^2 2\theta_{13} \sim 1\%$**

# First T2K Neutrino Event

**Feb 25, 2009:** A CC  $\nu_\mu$  interaction which produced  $\pi^0 \rightarrow \gamma\gamma$ :



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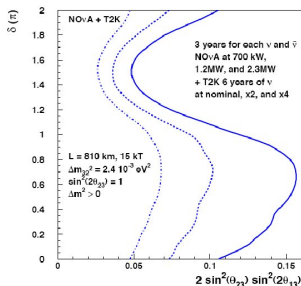
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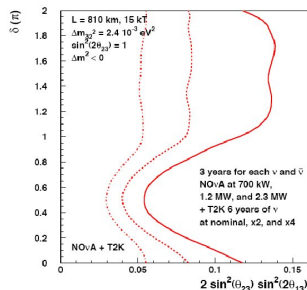
The NO $\nu$ A experiment is at a baseline of 810km off-axis to the NuMI beam. Detector is 15kT of active scintillator on the surface.

Operational by 2013. From G. Feldman:

## 95% CL Resolution of the Mass Ordering NO $\nu$ A Plus T2K



Normal Ordering



Inverted Ordering

Some sensitivity to mass hierarchy at large  $\theta_{13}$

# $\theta_{13}$ by 2016

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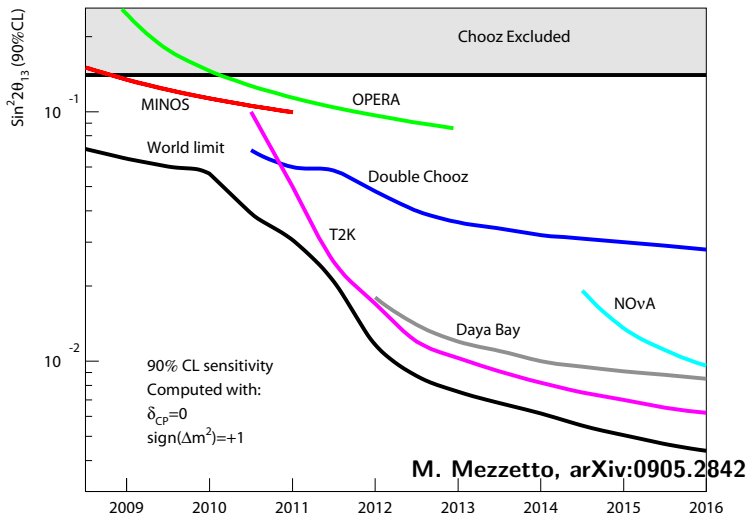
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# Matter Effect on Neutrino Oscillation

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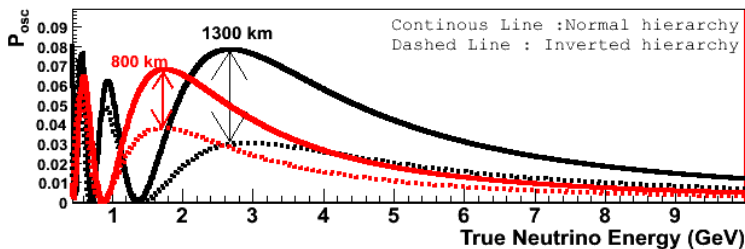
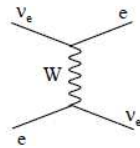
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**1978 and 1986:** L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of  $\nu_e$  on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index  $\Rightarrow$  neutrinos in matter have different effective mass than in vacuum. For  $P_{\text{osc}} = P(\nu_\mu \rightarrow \nu_e)$ :



With longer baselines we can use accel  $\nu$  to resolve  $\text{sign}(\Delta m_{31}^2)$ .

# CP Violation with long baseline experiments

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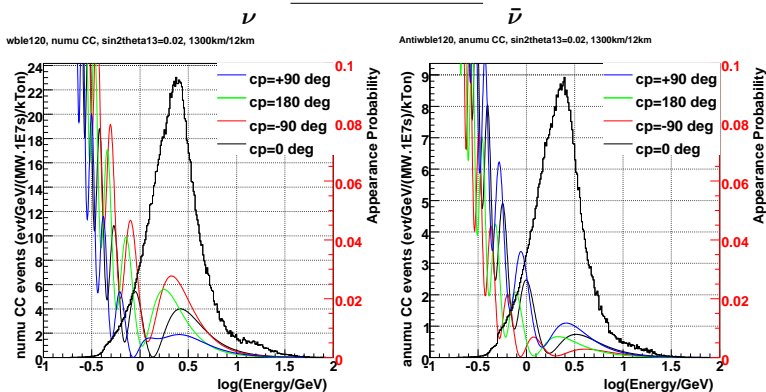
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*Appearance probabilities of  $\nu_\mu \rightarrow \nu_e$  for different values of the CP phase.  
A CP phase  $\neq 0, \pi$  implies CP is violated in the lepton sector.*

## Normal Hierarchy



**CP effects largest  $E_\nu < 3$  GeV.**

*Need high power wide-band beams with  $\nu$  and  $\bar{\nu}$  to resolve degeneracies*

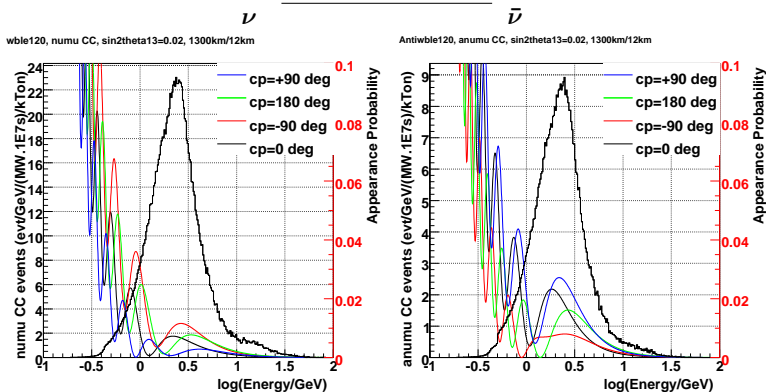
# CP Violation with long baseline experiments

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*Appearance probabilities of  $\nu_\mu \rightarrow \nu_e$  for different values of the CP phase.  
A CP phase  $\neq 0, \pi$  implies CP is violated in the lepton sector.*

## Reversed Hierarchy



**Matter effects large  $E_\nu > 1.5$  GeV.**

*Need high power wide-band beams with  $\nu$  and  $\bar{\nu}$  to resolve degeneracies*

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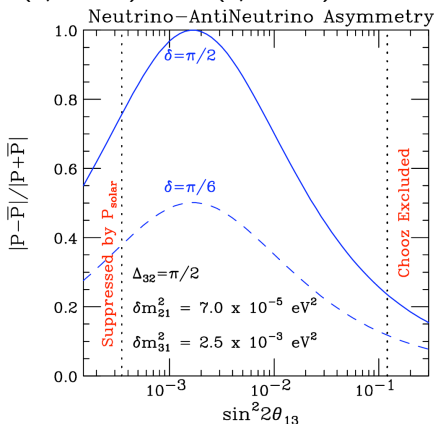
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## Asymmetry in $P(\nu_\mu \rightarrow \nu_e)$ and $\bar{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $\sin^2 2\theta_{13}$ :



**For values of  $\sin^2 2\theta_{13} > 0.002$ :**

**the CP asymmetry increases with smaller  $\theta_{13}$**

# Physics sensitivity vs baseline

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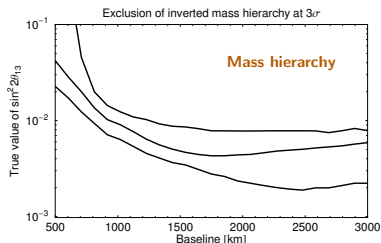
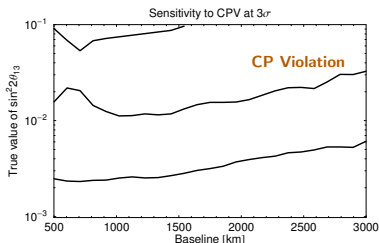
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Using a broad-band beam with a peak interaction rate at 2 GeV, FWHM=3 GeV, a parameterized water Cerenkov detector and exposure of 5MW.yr ( $\nu$ ) + 10 MW.yr ( $\bar{\nu}$ ) (V. Barger *et al.*, Phys. Rev. D 74, 073004 2006):



Minimum value of  $\sin^2(2\theta_{13})$  for which the sensitivity is  $> 3\sigma$   
for (best, 50%, worst) of  $\delta_{cp}$  values

Longer baselines = larger mass effects

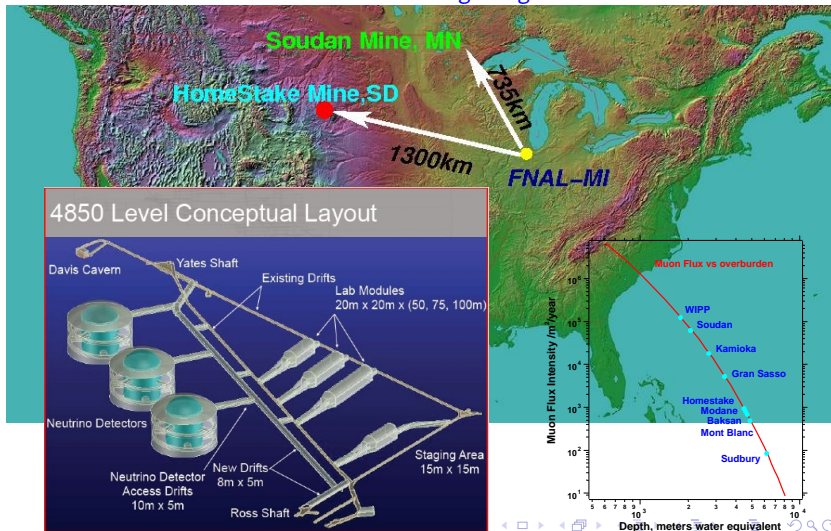
Best sensitivity is for baselines 1200 - 2500km

# The Long Baseline Neutrino Experiment

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*A Long Baseline Neutrino Experiment (LBNE) from Fermilab to megaton scale detectors at Homestake is now being designed. CDR late 2010.*



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# Fermilab Neutrino Beams: Future

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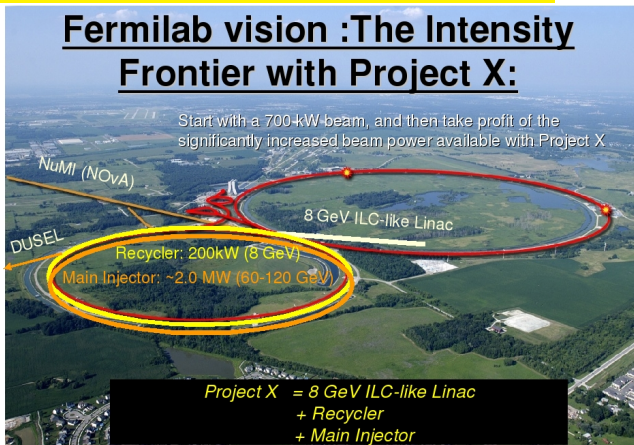
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The NuMI beamline uses a 300kW proton beam from the Main Injector (700 kW by 2012).

**NuMI is the most powerful  $\nu$  beamline operating today .**

## Fermilab vision :The Intensity Frontier with Project X:



**The proposed Project X at FNAL  $\rightarrow$  2MW with  $E_p = 60 - 120\text{GeV}$**

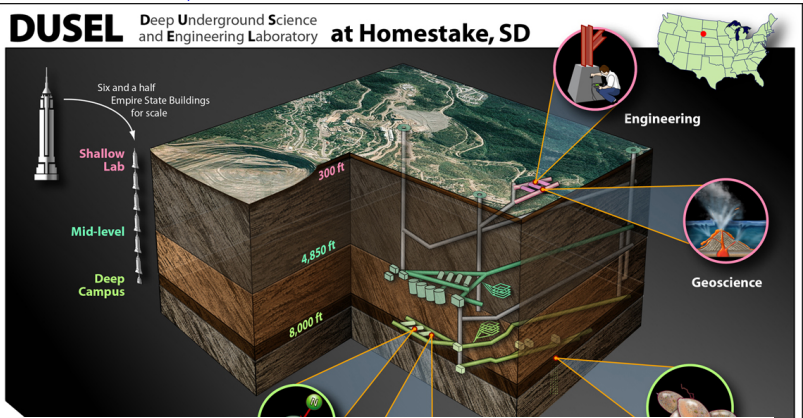
# Deep Underground Science and Engineering Laboratory

Neutrinos in the 21<sup>st</sup> Century

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*July 10, 2007: the National Science Foundation (NSF) selected the University California-Berkeley to produce a technical design for DUSEL at Homestake Mine, SD*

## **DUSEL** Deep Underground Science and Engineering Laboratory **at Homestake, SD**



**Dec 2010: National science board (NSB) preliminary design review.**

**FY13: Earliest construction funding if approved by NSF's NSB.**

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# DUSEL Detectors: Water Cerenkov

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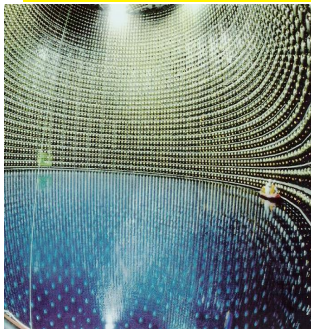
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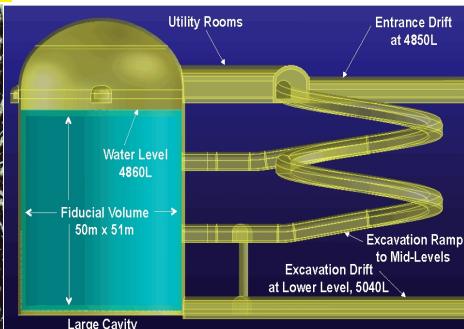
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**SuperKamiokande : 50kT**



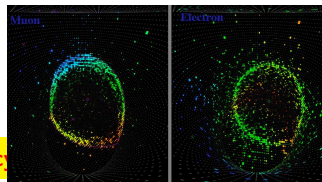
**DUSEL WCe Module : ~ 120 kT**



**3 100kT (fiducial) modules,  $\approx 55\text{m}$   
diameter,  $\approx 60\text{m}$  height, 60K 10"  
PMTs/module (25% coverage)**

**Known technology 3 – 4 $\times$  SuperK**

**Large NC  $\pi^0$  backgrounds, low efficiency**



# DUSEL Detectors: Liquid Argon TPC

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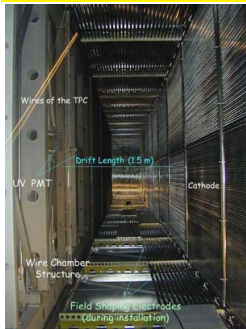
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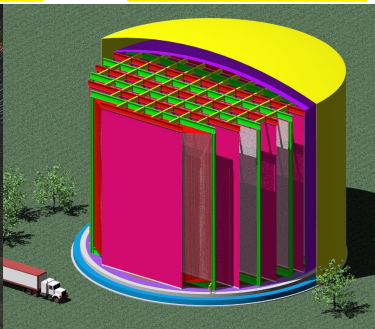
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**ICARUS module : 0.3kT**



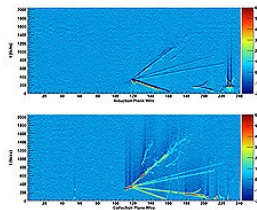
**DUSEL LAr : 50 kT**



**ArgoNeuT (175 litre) prototype in the  
NuMI beam →**

**High efficiency and purity**

**Requires 100× scale-up - unproven.**



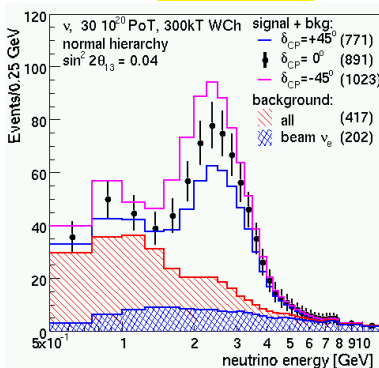
# LBNE/DUSEL spectra and event rates

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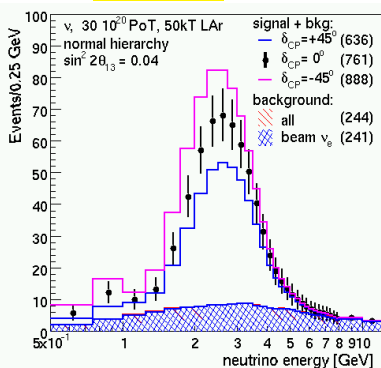
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**A preliminary on-axis wide-band beam for LBNE based on the NuMI focusing system has been developed. Water Cerenkov response is based on the SuperK MC. LAr is modeled as a near-perfect detector. Exposure is 3 MW.yr  $\nu$  with  $\sin^2 2\theta_{13} = 0.04$ ,  $\delta_{CP} > 0$ ,  $m_3 > m_1$**

**300 kT WCh**



**50 kT LAr**



A Brief  
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Neutrinos

Measurement  
of Neutrino  
Mass

Neutrino  
Mixing Expts -  
Current

The Search for  
 $\theta_{13}$

CP Violation  
and the Mass  
Hierarchy

DUSEL/LBNE  
Neutrino Expts.  
in Japan  
Superbeams in  
Europe

# Measurements of $\delta_{cp}$ in LBNE

Mark Dierckxsens

Neutrinos in  
the 21<sup>st</sup>  
Century

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Brookhaven  
National  
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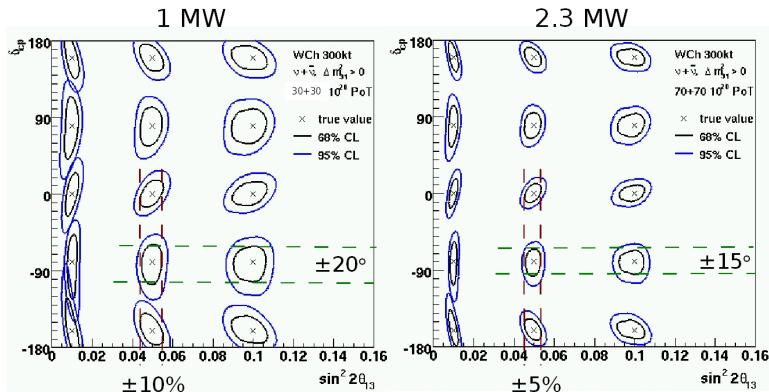
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with a 300 kT WCe detector and 3 yrs of  $\nu$  + 3 yrs of  $\bar{\nu}$  running:

$(\theta_{13}, \delta_{cp})$  Measurement



Precision measurement of  $\delta_{cp}$  for  $\sin^2 2\theta_{13} \geq 0.01$

# Long Baseline Projects in Japan

from talk by Koichiro Nishikawa, KEK

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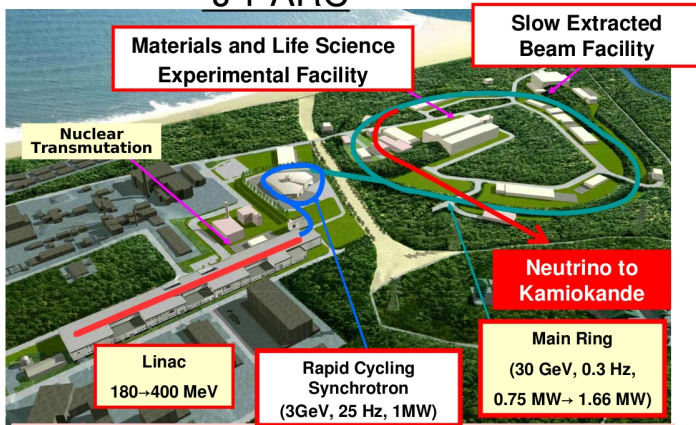
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## J-PARC



**J-PARC = Japan Proton Accelerator Research Complex**

**Joint Project between KEK and JAEA**

# 3 Long Baseline Scenarios

from talk by Koichiro Nishikawa, KEK

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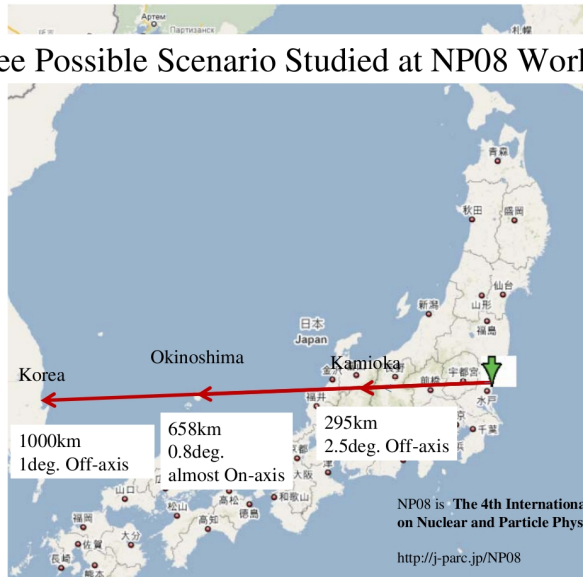
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## Three Possible Scenario Studied at NP08 Workshop



NP08 is The 4th International Workshop  
on Nuclear and Particle Physics at J-PARC

<http://j-parc.jp/NP08>

# Sensitivities of Scenario 3

from talk by Koichiro Nishikawa, KEK

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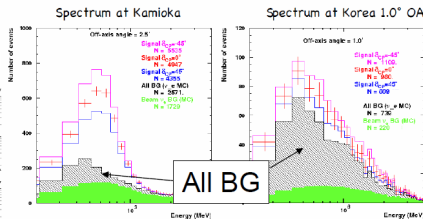
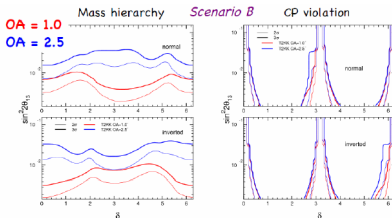
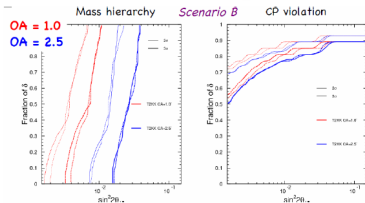
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## Scenario 3

- Cover 2<sup>nd</sup> Maximum @ Korea
  - Cover 1<sup>st</sup> Maximum @ Kamioka
  - 5 Years  $\nu$  + 5 Years  $\bar{\nu}$  Run 1.66MW
  - 270kt Water Cherenkov Detector each
- @ Korea, Kamioka

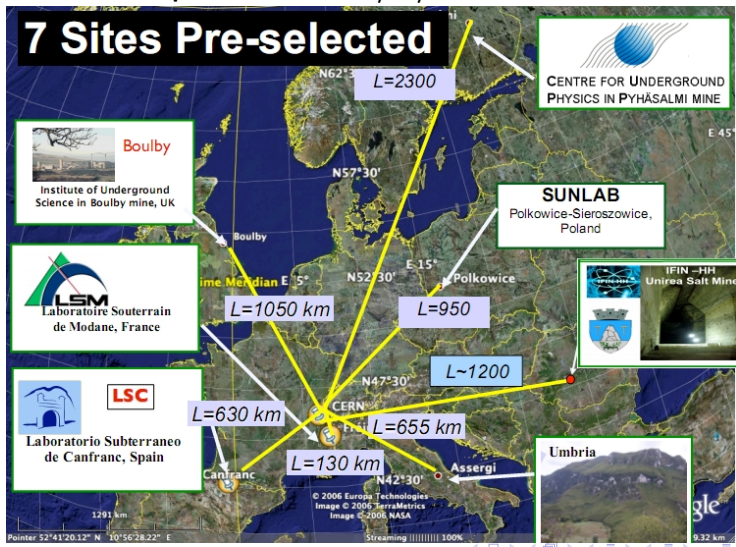


$\sin^2(2\theta_{13})=0.04$ , neutrino, normal hierarchy, Scenario B  
F.Dufour@NP08

(study is initiated by M.Ishitsuka et. al. hep-ph/0504026)

# Superbeams/Beta Beams/ $\nu$ Factories in Europe

F. Terranova's presentation on 15/11/09:



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# Summary and Conclusions

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*Neutrino's have non-zero mass, at least 3 flavors and large mixing, BUT:*

- How massive is a neutrino? Are neutrinos majorana particles?
- How small is  $\sin^2 2\theta_{13}$ ? Is it 0?, What is the mass hierarchy? Is there CP violation (and LFV) in the lepton sector?
- Are there only 3 generations of leptons?

**By 2025:**

Tritium end point experiments and  $0\nu\beta\beta$  experiments could determine  $\nu$  mass if  $\geq 0.2$  eV

New reactor and accelerator expts could determine if  $\sin^2 2\theta_{13} > 0.005$  and measure  $\delta_{cp}$  and the mass hierarchy if  $\sin^2 2\theta_{13} \geq 0.01$ . Sensitivity to new physics.

**Beyond 2025: neutrino factories and beta beams can push further:**

